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Research

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Observations on the Biology and Structure of three Dry Tropical Forests in South India

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Highlights:

1. Three large permanent study areas with mapped trees, shrubs and climbers in species-rich tropical dry deciduous forests on the South Indian Deccan Plateau provide the empirical evidence for this study.
2. The study areas are located in close vicinity to each other, but differ in species composition, structure and human impact.
3. We present a descriptive section with details of the 130 woody plant species that were assessed, and a quantitative section with examples of new modeling approaches.
4. The results are of interest to scientists involved in studies of diverse forests, not only in South India, but also in other regions of the world.

Abstract

Tropical dry deciduous forests are found in variable climates characterized by low rainfall where woody plants possess several functional traits that permit them to endure severe water stress for several months of the year. We present an assessment of species-rich Dry Tropical Forests of the South Indian Deccan Plateau based on three large, tree-mapped field plots located in close vicinity to each other. The study includes a descriptive section (details of 130 woody plant species) and a modeling section. The modeling section presents specific species-area relations, species abundance distributions and relationships between biological attributes and individual-based structural attributes. The Monod equation is found most suitable for modeling the species-area relations confirming previous studies. The shape of the species abundance distribution follows the Weibull model which represents an alternative to the traditional lognormal model; the Weibull parameters are related linearly to species richness which is a new finding.

Keywords: Tropical Dry Forest; Individual Structure, Forest Biology. long-term observational studies.

1 Introduction

Skilful and continuous observation provides essential evidence about dynamic processes in forest ecosystems (Sagarin and Pauchard, 2012). Examples of observational infrastructures are national forest inventories, field experiments and long-term observational studies. The objective of a national forest inventory is to prepare reports about the state of the forest resource at a given time and within a specific geographical context (Alekseev et al., 2019; Zeng et al., 2015). Field experiments are established to evaluate ecosystem response to specific treatments. Examples of manipulated field experiments include thinning and fertilizer treatments, short-rotation coppice trials and biodiversity–ecosystem functioning experiments. Forest observational studies complement forest inventories, and represent an important alternative to designed experiments (Condit, 2008). The system is not manipulated, trees are mapped, and field plots are large to capture effects of scale. Once established, re-measurements continue on the same site to assess the response to environmental change and human impact. A Forest Observational Study thus represents an important research infrastructure which provides a continuous flow of information about forest ecosystem response to disturbance and changing environmental conditions. More recently, such studies, established in natural and semi-natural forests in China, India, Africa and Mexico, have emerged as an important ecological infrastructure, complementing national forest inventories and designed experiments (Gadow et al., 2016). We present three examples of such studies established in the tropical dry deciduous forests of Southern India.

1.1 Tropical Dry Deciduous Forests of India

Forest classification systems were developed by experienced ecologists who were able to see differences and commonalities without getting bogged down by the dazzling variation in small-scale site conditions, community structures and species compositions. An example is the "official" forest classification system of India (Champion and Seth, 1968). The classification includes 14 forest types: *Wet Evergreen forest*, *Semi Evergreen forest*, *Moist Deciduous forest*, *Dry Deciduous forest*, *Littoral*, *Swamp/Mangrove forest*, *Dry Evergreen forest*, *Thorn forest*, *Sub tropical broad leaved forest*, *Subtropical Pine forest*, *Subtropical Dry Evergreen forest*, *Montane Wet Temperate forest*¹.

Hui and Richardson (2017) have shown how humans have been rearranging the world's biota following the era of European colonization, and especially through the post-second World War globalization. Humans

¹ A more recent classification by Reddy et al. (2015) includes 16 forest types: the 14 types by Champion and Seth (1968) with a modified wording, plus the categories "Savannah" and "Plantations".

have generated widespread biological invasions, leading to radical alterations to the functioning of ecosystems. *Acacia* species that are commercially important have been extensively planted in areas outside their natural range. *Eucalypts* have had modest invasive success despite their wide dissemination. *Casuarinas* have only recently been widely planted and little is known of their invasion ecology (Richardson et al., 2014). The primary forests of the world have not only been modified by human-mediated introductions of organisms to areas well outside their potential range; they have also been subject to extensive use and modification by unsustainable exploitation, illegal logging (Kleinschmit et al., 2016) or sophisticated "near-natural" management (Schütz et al., 2012). Marris (2013) proclaims such new ecosystems the "new normal" and calls on scientists and the public to embrace them and to "shake off the yoke of history".

Tropical dry deciduous forests are found in severe and extremely variable climates characterized by low rainfall and nutrient-poor soils where woody plants possess several functional traits that permit them to endure severe water stress for several months of the year. Canopy trees on drying soils typically respond to an extended drought by shedding their leaves (Borchert 1994). The lack of precipitation during several months of the year produces ecosystems that have adapted to survive a prolonged dry season. Deciduousness is the single most important adaptation among plants to the extended droughts. According to Singh and Chaturvedi (2017), these forests are among the most vulnerable and fragmented ecosystems in the world. In India, tropical dry deciduous forests are widely distributed over a large area. The tropical dry deciduous forests of the South Indian Deccan Plateau are represented by a few protected remnants of very particular ecosystems within densely populated areas. Fig. 1 shows the distribution of forest types prepared by the Forest Survey of India, and based on the classification by Champion and Seth (1968).

Figure 1. Distribution of forest types in India (map kindly provided by the Forest Survey of India, 2019). The study areas are located in the vicinity of Bengaluru in the South-Eastern part of the State of Karnataka.

Improved knowledge about the structure and dynamics of these forests, based on carefully selected observational field plots with mapped trees, will contribute to improved understanding and more effective conservation of this unique natural heritage. Three such protected areas, represent the empirical basis for this study.

1.2 Study Objectives

Studies of small-scale structural patterns in forests are still relatively rare (Hui et al., 1998; Aguirre et al., 2003; Pommerening and Grabarnik, 2019). Accordingly, the objective of this study is to contribute to improved understanding of these unique ecosystems by analyzing their biology and structure in some detail. Particular objectives are: 1. to apply specific methods of structural analysis based on the attributes of neighborhoods in the vicinity of individual trees; 2. to study relationships between the relative frequency and mean size of individual trees and the structural pattern in their immediate neighborhood; 3. to assess the biological and structural differences among the three study areas by comparing the species-area relationships and species abundance distributions. We expect that our study will contribute to improved understanding of these communities, raise awareness among the scientific community, and thus contribute to more effective conservation of these unique forests in South India. The methodological approaches, described in the ‘Methods’ section, are applied to the observations collected. The results are discussed and compared with the results of similar studies in other regions of the world.

2 Methods

2.1 Study Areas

Three large protected field plots were established by the Environmental Management and Policy Research Institute (EMPRI) in Bengaluru. The plots are designated Bugarikallu (Bg), Thalewoodhouse (Tw) and Doresanipalya (Do). GPS coordinates and elevations are presented in Tab. 1.

Table 1. GPS coordinates and elevations of the four cornerpoints (1..4) of the Bugarikallu (Bg), Thalewoodhouse (Tw) and Doresanipalya (Do) study areas. The distances are shown in the table at right (6.07 km between Bg1 and Tw1); (14.6 km between Tw1 and Do1); 20.62 km between Bg1 and Do1).

Location points	Latitude	Longitude	Elevation (m)	Accuracy (+/-meters)	Distance (km)	
Bugarikallu plot					6.07	20.65
Bg1	12° 42' 47.689" N	77° 32' 25.422" E	918.6	2.8		
Bg2	12° 42' 50.947" N	77° 32' 25.883" E	918.1	2.3		
Bg3	12° 42' 51.131" N	77° 32' 22.819" E	939	3.3		
Bg4	12° 42' 47.988" N	77° 32' 22.063" E	926.4	4.3		
Thalewoodhouse plot					14.61	
Tw1	12° 45' 52.236" N	77° 33' 33.023" E	906.4	3.1		
Tw2	12° 45' 52.157" N	77° 33' 36.515" E	936.4	6.3		
Tw3	12° 45' 48.312" N	77° 33' 36.205" E	912.6	5.4		
Tw4	12° 45' 49.097" N	77° 33' 33.210" E	906.7	5.1		
Doresanipalya plot						
Do1	12° 53' 32.525" N	77° 35' 26.520" E	918.9	9.6		
Do2	12° 53' 34.915" N	77° 35' 24.403" E	921.3	3.2		
Do3	12° 53' 37.118" N	77° 35' 26.876" E	920.4	8.6		
Do4	12° 53' 34.717" N	77° 35' 29.069" E	913.6	3.2		

The three study areas, shown in Fig. 2 in relation to their immediate surroundings, enjoy a high degree of protection. Heavy rainfall occurs during the months of September and October from the North-east monsoon and torrential rains from June to August from the South-west monsoon. Annual rainfall (based on South-West monsoon, North-East monsoon and Pre-monsoon) varies between 417 and 1494 mm with a mean of 869 mm measured during the period 1960 to 2016; occasionally the area receives heavy cyclonic rains in October and November. The mean annual temperature is around 24.7°C with a maximum 39.4°C and a minimum of 10.2°C. The soils have been classified as silty clay loam (Thalewoodhouse), sandy clay (Bugarikallu), and loamy sand/sandy loam (Doresanipalya). Detailed descriptions are presented by Raju (2014).

Figure 2. Location of the three study sites to the south of the Bengaluru city center. Google map images of the study sites and their immediate surroundings are shown in the three circles.

The Doresanipalya plot is surrounded by urban settlement with a high population density in the suburbs of the city of Bengaluru. Thalewoodhouse and Bugarikallu are located in the Bannerghatta National Park which is shown in green color in Fig. 2. All three sites are strictly protected, and located in close vicinity to each other (distances are shown in Tab. 1.).

2.2 Descriptive Methods

Descriptive details for each woody plant species will be developed, separately for each plot, including plant taxonomies, taxonomic ratios and number of introduced or invasive species. We will also present a brief

summary of the 22 species of climbers encountered in the three study areas. The climbers are classified based on the mode of climbing as *twiners*, *lianas* and *stragglers*.

2.3 Quantitative Methods

2.3.1 The Species-Area Relationship

To allow comparisons of the study sites in terms of species richness, it is necessary to develop a relation between the contiguous plot area and the number of species in each plot. A number of models have been proposed to describe the species-area relation (Monod, 1950; de Caprariis *et al.*, 1976; Gitay *et al.*, 1991; Williams, 1995; Tjørve, 2003). Asymptotic functions are appropriate in very large plots where all species are likely to be captured by the samples. The power function is more suitable for small plot sizes where the maximum number of species is unknown. The following function, proposed by Monod (1950), represents a suitable compromise and will be used in our study to estimate the species-area relation:

$$S = \frac{a \cdot A}{1 + b \cdot A} \quad (1)$$

where a , b are empirical parameters; S is number of species; A is a contiguous forest area (m^2). We derive such a species-area relation by assigning sample plots of increasing size to random positions within the study area. The sampled area and associated number of species are used to derive a species-area relation (SAR) for the whole plot. Eq. 1 has the following properties: 1) when $A=0$, then $S=0$; 2) S increases with increasing A , until an asymptotic value ($S_{\max}$) is reached; 3) the estimated maximum number of tree species equals a/b , which is a useful property.

2.3.2 The Species-Abundance Distribution

The species abundance distribution (SAD) describes the abundances of all species recorded within a forest community of interest. The SAD may explain processes of community assembly, and is believed to be one of the most ubiquitous patterns in ecology (Matthews and Whittaker, 2014). We estimate the SAD using the Weibull distribution:

$LN = k \cdot e^{(-SR/b)^c}$	2
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where LN is the estimated logarithm of the number of individuals; k is the log (number of individuals of species 1, i.e. the species with the maximum number of individuals). SR is species rank; b and c are estimated parameters.

2.3.3 Forest Structure: cell-based

Information about ecosystem structure presents a useful complement to the biological analysis of species richness and abundance patterns. A first approach to characterizing structure is to subdivide a study area into smaller cells (or quadrats). The subdivision into smaller spatial units facilitates detailed analysis of small scale patterns, as well as comparison among different study areas. Fig. 3 presents a visual impression of the spatial species mix and the tree size distribution in the three study areas. Some species are size-dominant represented by large individuals: *Ficus benghalensis* in Bugarikallu, *Terminalia paniculata* and *Eucalyptus tereticornis* in Doresanipalya, and *Ficus microcarpa*, *Terminalia arjuna*, *Premna tomentosa*, and *Albizia odoratissima* in Thalewoodhouse.

Figure 3. A general impression of the spatial species mix and tree size distribution in the three study areas. Each species has a unique color across all three study sites. The subdivision into smaller cells facilitates analysis of the spatial distribution (and scale dependence) of particular patterns.

The bottom row in Fig 3 shows a subdivision into smaller cells. We will analyze the cell-based distributions of the following seven variables in each study area:

BA _{ha} :	basal area in m ² per ha
N _{ha} :	number of woody plants per ha
S:	cell richness (number of species in cell)
D _q :	quadratic mean dbh (cm)
CVD:	dbh coefficient of variation
M:	cell Mingling (the ratio number of species/number of individuals in cell)
CE:	Clark & Evans index in cells

The absolute discrepancy between the distributions of these variable in two study areas was calculated using the following criterion:

$$d = \frac{1}{2} \sum_{i=1}^m |p_i - q_i| \quad (1)$$

where p_i and q_i are the relative frequencies in the i 'th frequency class of a particular variable in pairs of study areas that we wish to compare. The absolute discrepancy d thus represents the proportion of a particular frequency in one study area that has to be changed such that both distributions (ordered by specific frequency classes) are identical. Our analysis is limited to 20 x 20m cells.

2.3.4 Forest Structure: Individual-based

Forest structure may also be characterized by evaluating the immediate neighborhood of selected tree species. We will use the variables *Mingling*, *Dominance* and *Size Differentiation* to describe the specific neighborhood constellations of each individual species. Three measures of species-specific structural diversity are defined as follows (Gadow, 1993; c.f. Pommerening et al., 2020):

Mingling (M)	Dominance (D)	Size Differentiation (T)
Mean heterospecific fraction of trees among the k nearest neighbours of a given tree i .	Mean fraction of n nearest neighbors with a dbh $<$ (dbh of the reference tree).	Mean of the ratio of smaller and larger tree sizes u of the k nearest neighbours subtracted from one.
$M_i = \frac{1}{k} \sum_{j=1}^k 1(\text{species}_i \neq \text{species}_j)$	$D_i = \frac{1}{k} \sum_{j=1}^k 1(\text{dbh}_i > \text{dbh}_j)$	$T_i = 1 - \frac{1}{k} \sum_{j=1}^k \frac{\min(u_i, u_j)}{\max(u_i, u_j)}$

The three variables represent a system for characterizing structural patterns at high resolution in a consistent set where all the variables assume values in the interval [0,1]. *Mingling* defines the degree of spatial segregation of the tree species (Gadow 1993; Aguirre et al., 2003; Pommerening and Grabarnik, 2019). *Dominance* measures the size dominance of the reference tree in relation to its immediate surrounding (Hui et al., 1998). *Size Differentiation* measures the variation of tree sizes between the reference tree and its nearest neighbors (Pommerening et al., 2020). Instead of selecting a particular reference species (as was done in this study), we may wish to select all trees that belong to a particular family, or all dominant trees of a given species, as reference trees with the aim to study their particular neighborhoods.

Note that reference trees located close to the plot edge may produce a biased estimate of the neighborhood constellation because some of the real nearest neighbors may be located outside, beyond the plot perimeter. To avoid such bias, edge correction has to be employed. The simplest method involves a definition of a buffer around the plot edges. Edge correction, ensuring that the distance to the plot boundary of each reference tree must be greater than the distance to its 4th neighbor, is applied in this study to avoid biased estimates of the neighborhood parameters.

3 Results

We present descriptive and modeling results. The descriptive results are assumed to be of interest to biologists interested in taxonomic detail, while the modeling results allow comparisons among forest structure in a wider context.

3.1 Descriptive Results

3.1.1 Woody Plant Species

Appendix 1 presents a table with details for each species, separately for each plot. The information includes parameters that are assessed in routine forest inventories (mean dbh, trees per ha) as well as the means of the structural parameters Mingling (M), Dominance (D) and Size Differentiation (T). A summary of the details in Appendix 1 is presented in Tab. 2.

Almost 70 percent of all the tree and shrub species encountered in the three study sites occur on all three sites. Thirty one percent,(181-137) of 130, of species are not common to all three sites.

Table 2. Summary of the species-specific details listed in Appendix 1.

Study Site	Tree,shrub & climber species	number of families	species per family	number of species introduced/invasive
Bugarikallu	76	35	2.17	2
Doresanipalya	46	20	2.3	10
Thalewoodhouse	69	28	2.46	1
3 Sites combined	130	40	3.25	11

Climbers are plants that are rooted in the ground but use other plants for support. The climbers that were identified in the three permanent study areas were classified based on the mode of climbing as twiners, lianas and stragglers. *Lianas* are long stemmed woody plants that use the support of a tree moving up to the canopy in search of sunlight. *Twiners* (or stem climbers) are "twining" themselves spirally around a supporting tree. They may reach the canopy, but are mostly restricted to the understorey. *Stragglers* (ramblers) are plants that do not climb but somehow manage to support themselves by clinging to the trunks, stems, or branches of other plants. Stragglers have specialized organs, such as prickles, spines or thorns that are used for support. Twenty two species of climbers were found in the three permanent study areas. (Tab. 3).

Altogether 356 individual climbing plants belonging to 12 species occur in the Thalewoodhouse study area. Bugarikallu has 350 individual climbers belonging to 15 species while Doresanipalya has 272 climbing individuals belonging to 7 species. The dominant climber species in Thalewoodhouse are *Hiptage benghalensis*, a liana which is often found in the upper canopies, and two stragglers: *Ziziphus oenoplia* and *Jasminum angustifolium*.

The most frequent climbers in Bugarikallu are three stragglers: *Pterolobium hexapetalum*, *Jasminum angustifolium* and *Ziziphus oenoplia*. The endangered twiner *Decalepis hamiltonii* (IUCN Red list of Threatened Species) is also found in Bugarikallu. *Ziziphus oenoplia* is the most frequent climber in Doresanipalya followed by *Gymnema sylvestre*, a well-known medicinal plant.

3.1.2 Exotics: Introduced/Invasive Species

Two non-native woody plant species occur in Bugarikallu (*Cassia siamea*; *Eucalyptus globulus*), ten in Doresanipalya (*Acacia auriculiformis*; *Anacardium occidentale*; *Annona squamosa*; *Cassia siamea*; *Cassia spectabilis*; *Eucalyptus tereticornis*; *Grevillea robusta*; *Jacaranda mimosifolia*; *Leucaena leucocephala*; *Psidium guajava*), and one in

Thalewoodhouse (*Cassia spectabilis*). Numerous rare species are found in each of the three study areas. Many rare species are only represented by one individual (refer to Appendix 1 for details).

Table 3. Details of the 22 species of climber found in the three study areas (Thalewoodhouse TW; Bugarikallu BG; Doresanipalya DO).

Species	TW	BG	DO	Characteristics
<i>Acacia concinna</i>	5	10	0	Shrubby straggler with prickles (understorey & canopy)
<i>Argyrea cuneata</i>	0	2	1	Stout climbing shrub (understorey & canopy)
<i>Argyrea sericea</i>	0	0	8	Stout Climber (on the ground, understorey & canopy)
<i>Cansjera rheedei</i>	0	3	0	Climber (canopy & understorey)
<i>Capparis sepiaria</i>	0	3	0	Scandent shrubs with spines (understorey & canopy)
<i>Celastrus paniculatus</i>	1	5	0	Straggling shrub (understorey)
<i>Decalepis hamiltonii</i>	0	1	0	Endangered Twining shrub (Rocks, understorey)
<i>Embelia viridifolia</i>	0	0	1	Woody climbers (understorey)
<i>Gynema sylvestre</i>	0	4	26	Twining subshrub (understorey & Canopy)
<i>Hiptage benghalensis</i>	121	0	0	Large woody climber-twiner (Upper canopy)
<i>Ichnocarpus frutescens</i>	14	0	0	Climber (understorey & canopy)
<i>Ipomoea illustris</i>	1	0	0	Climber (understorey)
<i>Jasminum angustifolium</i>	40	88	0	Straggling shrub (understorey)
<i>Mimosa rubicanlis</i>	18	0	0	Straggling shrub with prickles (understorey)
<i>Pterolobium hexapetalum</i>	0	169	0	Prickly straggler (understorey)
<i>Scutia myrtina</i>	1	17	24	Spiny straggling shrub (understorey & canopy)
<i>Secamone emetic</i>	0	1	0	Scandent shrubs (understorey & canopy)
<i>Toddalia asiatica</i>	2	8	0	Straggler with recurved prickles (understorey & canopy)
<i>Tylophora indica</i>	0	0	4	Slender pubescent climber (understorey & canopy)
<i>Ventilago maderaspatana</i>	11	1	0	Woody climbing shrub (Upper canopy)
<i>Ziziphus oenopia</i>	139	37	208	Scandent shrub with thorns (understorey)
<i>Ziziphus rugosa</i>	3	1	0	Straggling shrub with spines (understorey)
Total individuals (total species)	356 (12)	350 (15)	272 (7)	

3.2 Quantitative Results

3.2.1 Neighborhood-based Results

Each tree species is characterized by an average diameter at breast height (dbh), a specific contribution to the total density of woody plants, and by a species-specific neighborhood constellation. The relevant details are found in Appendix 1. The variable Mingling obviously assumes a maximum value of 1.0 for all species that occur with only 1 individual, e.g. *Acacia leucophloea*, *Atalantia monophylla*, *Carmona retusa*, *Cipadessa baccifera*, *Decalepis hamiltonii*, *Phyllanthus indofischeri* and several others in Bugarikallu. The mean Mingling-values are low for species occurring with a high frequency (e.g. 0.45 for *Ixora nigricans* with 1033 individuals; 0.57 for *Anogeissus latifolia* with 546 individuals; 0.51 for *Pterolobium hexapetalum* with 400 individuals; 0.61 for *Canthium dicoccum* with 208 individuals) in Bugarikallu. Species occurring with a high relative frequency are likely to have more conspecific neighbors. *Premna tomentosa* and *Shorea roxburghii* in Bugarikallu, or *Glochidion zeylanicum* in Thale have low mingling values despite their low frequencies. Such unexpected constellations indicate spatial aggregation within conspecific clusters.

3.2.2 Cell-based Results

The absolute discrepancies among the three study areas, based on the seven cell variables, are presented in Tab. 4.

Table 4. Absolute discrepancies among the three study areas, based on the seven cell variables that were used in this study.

Variable	Bugari Thale	Bugari Doresan	Doresan Thale
BA_ha	0.64	0.52	0.60
N_ha	0.52	0.36	0.32
Richness	0.32	0.76	0.60
Clark_Evans	0.08	0.48	0.44
Dq	0.68	0.48	0.48
CVD	0.84	0.76	0.68
Mingling	0.36	0.28	0.64

Bugarikallu and Thalewoodhouse differ most in density (BA_ha), quadratic mean dbh (Dq) and diameter coefficient of variation (CVD). Bugarikallu and Doresanipalya differ in terms of species richness and diameter coefficient of variation. Doresanipalya and Thalewoodhouse differ most by density, richness, diameter coefficient of variation and cell mingling.

3.2.3 The Species-Area Relation

The estimated parameters a and b of the Monod model, and the graphs of the fitted functions for each field plot, are presented in Tab. 5.

Table 5. Estimated parameters a and b of the Monod model for the three study areas.

Study Area	Species Richness	SAR (Monod)	
		a	b
Doresanipalya	46	0.04146	0.000816
Bugarikallu	76	0.11790	0.001513
Thalewoodhouse	69	0.02996	0.000449

By solving the Monod equation for any arbitrary area, an estimate of species richness for that area is obtained. The parameters in Tab. 5 can thus be used to make species richness values comparable among different plot sizes.

3.2.4 The Species Abundance Distribution

Species abundance curves provide information about how communities differ in the way they are organized. The species abundance distribution generally takes a curve shape that is defined by many rare species and a few common ones (McGill et al., 2007; Matthews and Whittaker, 2014). Fig. 4 presents the three graphs of the fitted SAD's.

Figure 4. *Species Abundance Distributions of the three study areas. When plotted in this way, relative species abundances from very different data sets show similar patterns.*

The Weibull parameter b increases with increasing number of species, and can be estimated by the following linear function: $\text{Weibull } b = -0.5862 + 0.3942 * (\text{number of species per ha})$.

The shape of the species abundance distribution is influenced by the degree to which common species dominate the community, and by the number of very rare species (McGlenn et al. 2019). Communities that are strongly dominated by one or a few species often have low species diversity overall. Our results confirm this observation.

4 Discussion

A large proportion of the world's population relies directly on forests for livelihood. Sustaining these ecosystems is thus often a matter of survival. Humans have to accept the premise that the allegorical “Garden of Eden” is a dreamworld. Human impact on our planet is so overwhelming that the current period in the Earth’s history has been named *Anthropocene* – the age of humans. Crutzen (2002) concluded that mankind has been and will remain a major environmental force in the future. In this study, we present some examples of evaluating the biology, density and structure of complex forest ecosystems. These methods are part of a scientific toolbox that enables us to make value judgments, and to choose between alternative courses of action.

Planted forests attracted much interest during the 1960's and 1970's of the past century, our study areas are self-regenerating forests. Self-regenerating forests are a vast resource. They include complex primary forests as well as exploited and degraded ecosystems, forests subject to sophisticated selection management systems, or communities dominated by invasive species. New initiatives are required to establish particular

research infrastructures, and develop new analytical tools to improve our understanding of the biology, structure and dynamics of these complex ecosystems.

4.1 *Tree Species Richness and Diversity*

In community ecology there has been more attention paid to the measurement of species diversity than to almost any other parameter. Accordingly, there is a rich literature on diversity, with many contradictory recommendations (Hubálek, 2000). Most popular are Hill's numbers as easily interpreted measures of diversity. This includes the exponential form of the Shannon² function (Hill's N1) and the reciprocal of Simpson's index (Hill's N2). The choice depends on whether more weight is given to the rare species (N1) or to the common species (N2).

Traditional indices of biodiversity incorporate only the numbers of species and their frequencies without considering the biological differences among the species. Ganeshaiah et al. (1997) proposed a measure of community diversity known as the "Avalanche index". The Avalanche measure, recently "revived" by Hao et al. (2019), is defined as follows:

$$A = \sum_{i=1}^S \sum_{j=i+1}^S p_i * d_{ij} * p_j \quad 3$$

where S is the total number of tree species, p_i and p_j are the relative frequencies of species i and j in the community, and d_{ij} is a measure of the taxonomic distance between species i and j . The Avalanche diversity does not only account for the number of species and their frequencies, but also considers the taxonomic hierarchy. The Shannon entropy would be the same for two communities A and B if both have the same number of species occurring with the same frequencies. The Avalanche diversity in B would exceed that in A if the number of genera would be greater in B than in A, because the Avalanche index captures the intra-community biological variation. The Avalanche is not only useful as an index of diversity, but also as a measure that can be used to assess the dissimilarity of two forest communities (Hao et al., 2019; see also Talents et al., 2005). Tab. 6 shows that the Hill D1 (the exponent of the Shannon index) is almost identical for Bugarikallu and Thalewoodhouse although Bugarikallu has more species than Thalewoodhouse but a lower evenness. This result is supported by the fact that the Avalanche index for Thalewoodhouse exceeds

² This index is sometimes called "Shannon-Wiener" and sometimes "Shannon-Weaver" Index. The names Wiener and Weaver are similar (sometimes Wiener is spelt incorrectly as Weiner). We follow Spellerberg and Fedor (2003) by referring simply to the "Shannon Index".

that for Bugarikallu. The number of species per family is 2.17 in Bugarikallu, and 2.46 in Thalewoodhouse (Tab. 2) which explains the slightly greater Avalanche value for Thalewoodhouse.

Table 6. Species richness per ha and three measures of diversity: the Shannon entropy and its exponent value, Hill number D1, and the Avalanche index for the three plots.

Study Area	TreeShrub, & Climber Species Richness	Shannon	Hill D1	Avalanche
Doresanpalya	46	2.263	9.61	0.321
Bugarikallu	76	3.078	21.71	0.345
Thalewoodhouse	69	3.069	21.52	0.352

Species richness depends on plot size. One way to derive a common estimate of species richness, is to develop a species-area relation (SAR) for each plot individually, and to estimate richness for a particular standard area, such as 1 hectare. The results from this study thus provide a useful basis for comparison with other ecosystems, and for testing general assumptions presented in previous studies (e.g. Preston, 1962; May, 1975; Hubbell, 2001).

A quantity of considerable practical relevance is the minimum contiguous area required to capture all the species within a particular region. Gadow and Hui (2007) found a relationship, based on tree-mapped field plots assessed in various regions of the world, between the maximum number of tree species within a forest region (S_{max} , which is often known), and the minimum contiguous area required to capture all the species within that region (A_{min} , measured in m^2). The minimum contiguous area was estimated in their study by the function $A_{min} = 487.8 \times S_{max}^{0.524}$. This result implies that, for contiguous forest areas, the form of the species-area relationship is directly defined by the observed species abundance and the maximum number of species in the region. Assuming that the maximum number of species in the region around Bengaluru is 130, the estimate of the minimum contiguous area to capture all species would be $487.8 \times 130^{0.524} = 6250.98 m^2$ in each of the three plots. This area is less than that of the study areas ($10000 m^2$), but inspection of the graphs of the SAR functions reveals that the estimate is quite reasonable.

4.2 Specific Relationships

The relationships between variables that are often assessed in routine forest inventories (mean dbh and number of trees), and neighborhood parameters (Mingling and Dominance) are shown in Fig. 5 for the three study areas. The relation between the number of trees per ha and the mean neighborhood mingling is estimated using a power function. The relation between the mean dbh (cm) and the mean neighborhood

Dominance is estimated using the Monod function. Figure 5 presents the graphs and the equations of these relationships for each study area.

	Bugarikallu	Doresanipalya	Thalewoodhouse
relative frequency vs neighborhood mingling, all species
	$M = \exp(-2.53 * N^{0.30})$	$M = \exp(-1.12 * N^{0.46})$	$M = \exp(-1.85 * N^{0.55})$
mean dbh vs neighborhood dominance, all species
	$D = 0.28 * x / (1 + 0.26 * x)$	$D = 0.27 * dbh / (1 + 0.23 * dbh)$	$D = 0.034 * x / (1 + 0.35 * x)$

Figure 5. The relationships between species-specific variables in the three plots. Shown are the number of trees per ha and the mean neighborhood mingling with the estimated non-linear model below (upper row); the mean dbh (cm) and the mean neighborhood Dominance with the estimated Monod model (below).

The structural parameters provide additional information about the close-range neighborhood of each species. Not surprisingly, high correlation values are found between tree density and mingling for individual species. No relation was found regarding the dbh differentiation (I). Tree size variation within neighborhood groups was independent of tree size and the degree of species mingling.

4.3 Conclusions

Forests include a great variety of ecosystems where plants and animals interact with their physical environment. The challenge is to sustain their ability to function, to adapt to changing climates, and to satisfy a variety of human needs. Permanent field plots with mapped trees provide an essential "green infrastructure" for observing the dynamic evolution of such ecosystems. This study presents three

examples of tropical dry forests in South India with details of the biological and fine-scale structural characteristics of the 130 woody plant species. The Weibull model was used to characterize the species abundance distribution. Non-linear relationships were established between close-range neighborhood structure, species abundance and relative dominance. A previously published general assumption for estimating the minimum contiguous area required to capture all species based on regional species richness was confirmed.

5 Declarations

5.1 Ethics approval and consent to participate

Not applicable

5.2 Consent for publication

Not applicable

5.3 Availability of data and material

The datasets used and/or analysed during the current study are available from the corresponding author on request.

5.4 Competing interest

The authors declare that they have no competing interests.

5.5 Funding

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5.6 Authors contributions

All authors contributed equally; KVG analyzed and interpreted the data. All authors read & approved the final manuscript.

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6 References

- Aguirre O, Hui GY, Gadow KV, Jimenez J (2003) Comparative analysis of natural forest sites in Durango, Mexico. *Forest Ecology and Management* 183:137-145.
- Alekseev, Alexander, Erkki Tomppo, Ronald E. McRoberts and Klaus v. Gadow (2019) A constructive review of the State Forest Inventory in the Russian Federation. *Forest Ecosystems* 2019:6.
- Borchert, R. (1994) Water storage in soil or tree stems determines phenology and distribution of tropical dry forest trees. *Ecology* 75:1437–1449.
- Bray JR and Curtis JT (1957) An ordination of the upland forest communities of southern Wisconsin. *Ecological monographs* 27(4):325-349.
- Champion HG, Seth SK (1968) A Revised Survey of the Forest Types of India. Govt. of India Press, Delhi, 404 p
- Clarke KR, Warwick RM (1998) A taxonomic distinctness index and its statistical properties. *Journal of applied ecology* 35(4):523-531.
- Clarke KR, Warwick RM (2001) A further biodiversity index applicable to species lists: variation in taxonomic distinctness. *Marine Ecology Progress Series* 216:265-278.
- Condit, R. (2008) Methods for estimating above-ground biomass of forest and replacement vegetation in the tropics. Center for Tropical Forest Science Research Manual, 73 pages.
- de Caprariis P., Lindemann R.H., Collins, C.M. (1976) A method for determining optimum sample size in species diversity studies. *Mathematical Geology* 8(5): 575-581.
- Dunstan PK, Bax NJ, Foster SD, Williams A, Althaus F (2012). Identifying hotspots for biodiversity management using rank-abundance distribution. *Diversity and Distributions*, 18: 22-32.
- Gadow K.v. (1993) Zur Bestandesbeschreibung in der Forsteinrichtung (engl: How to describe a forest). *Forst und Holz* 48(21):602-606
- Gadow, K. v., Hui, G. Y (2007) Can the tree species-area relationship be derived from prior knowledge of the tree species richness? *Forestry Studies / Metsanduslikud Uurimused* 46: 13–22.
- Gadow, K. v., Xiu Hai Zhao, V. P. Tewari, Chun Yu Zhang, Ashwani Kumar, Jose Javier Corral Rivas and Rajesh Kumar (2016) Forest observational studies: an alternative to designed experiments. *European Journal of Forest Research* 135(3): 417-431.
- Ganeshiah KN, Chandrashekara K, and Kumar ARV (1997) Avalanche index: a new measure of biodiversity based on biological heterogeneity of the communities. *Current Science* 73(2):128-133.

- Ganeshaiah KN, and Shaanker RU (2000) Measuring biological heterogeneity of forest vegetation types: avalanche index as an estimate of biological diversity. *Biodiversity & Conservation* 9(7):953-963.
- Gitay, H., Rexburg, S.H., Wilson, J. B. (1991) Species-Area relation in a New Zealand tussock grassland, with implications for nature reserve design and for community structure. *J. Veg. Sci.* 2:113-118.
- Hao, Minhui; J. Javier Corral-Rivas; M. Socorro González-Elizondo; K. Narayanagowda Ganeshaiah; M. Guadalupe Nava-Miranda; Chunyu Zhang, Xiuhai Zhao and Klaus von Gadow (2019) Assessing biological dissimilarities between five forest communities. *Forest Ecosystems* 2019, 6:30.
- Hao, Minhui; Kotiganahalli Narayanagowda Ganeshaiah, Chunyu Zhang, Xiuhai Zhao, Klaus von Gadow (2019) Discriminating among forest communities based on taxonomic, phylogenetic and trait distances. *Forest Ecology and Management* 440, 2019, 40–47
- Hayden, B., and Greene, D.F. (2008) The ecology of tropical dry forests. A chapter in the *Encyclopedia of Tropical Ecology and Conservation* (UNESCO).
- Hubálek, Zdeněk (2000) Measures of species diversity in ecology: an evaluation. *Folia Zool.* – 49(4): 241–260.
- Hubbell, S. P (2001) *The unified Neutral Theory of Biodiversity and Biogeography*. Princeton University Press. Princeton u. Oxford: 375 p.
- Hubbell, S. P (2001) *The unified Neutral Theory of Biodiversity and Biogeography*. Princeton University Press. Princeton u. Oxford: 375 p.
- Hui, Cang and DM Richardson (2017) *Invasion Dynamics*. Oxford University Press: 322 p.
- Hui, G.Y., Albert, M, Gadow, K. v. (1998) Das Umgebungsmaß als Parameter zur Nachbildung von Bestandesstrukturen [Dominance as a measure of Forest Structure]. *Forstwissenschaftliches Centralblatt* 117(1): 258-266.
- Kleinschmit, D; Stephanie Mansourian, Christoph Wildburger and Andre Purret (eds.) (2016) *Illegal Logging and Related Timber Trade – Dimensions, Drivers, Impacts and Responses*. A Global Scientific Rapid Response Assessment Report. IUFRO World Series Volume 35. Vienna. 148 p.
- Komonen A, Elo M (2017) Ecological response hides behind the species abundance distribution: community response to low-intensity disturbance in managed grasslands. *Ecology & Evolution*, 7(20): 8558-8566.
- Lawton, J. H. (1999) Are there general laws in ecology? *Oikos* 84:177-192.
- Marris, E. (2013) Perspective: Coming of Age in a Trash Forest. In: Hobbs et al. 2013, Wiley-Blackwell, Chapter 29: 245
- Matthews TJ, Borges PAV, Whittaker RJ (2014) Multimodal species abundance distributions: a deconstruction approach reveals the processes behind the pattern. *Oikos*, 123: 533-544.
- Matthews, T. J., and Whittaker, R. J. (2014) Fitting and comparing competing models of the species abundance distribution: assessment and prospect. *Frontiers of Biogeography*, 6(2), 67-82.
- McGill BJ, Etienne RS, Gray JS, Alonso D, Anderson MJ, Benecha HK, Dornelas M, Enquist BJ, Green JL, He FL, Huilbert AH, Magurran AE, Marquet PA, Maurer BA, Ostling A, Soykan CU, Ugland KI, White EP (2007) Species abundance distributions: moving beyond single prediction theories to integration within an ecological framework. *Ecology Letters* 10: 995-1015.
- McGlinn DJ, Xiao X, May F, Daniel J. McGlinn Xiao Xiao Felix May Gotelli NJ, Engel T, Blowes SA, Knight TM, Purschke O, Chase JM, McGill BJ (2019) Measurement of Biodiversity (MoB): A method to separate the scale-dependent effects of species abundance distribution, density, and aggregation on diversity change. *Methods in Ecology and Evolution* 10: 258-269.
- Miles, L., A. C. Newton, R. S. DeFries, C. Ravilious, I. May, S. Blyth, V. Kapos, and J. E. Gordon (2006) A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* 33:491-505.
- Monod, J (1950) La technique de culture continue, théorie et applications. *Annales de l'Institut Pasteur* 79: 390–410.
- Pommerening, A. and Grabarnik, P (2019) *Individual-based Methods in Forest Ecology and Management*. Springer Nature: 411 p.

- Pommerening, A., Wang, H. & Zhao, Z. (2020) Global woodland structure from local interactions: new nearest-neighbour functions for understanding the ontogenesis of global forest structure. *Forest Ecosystems* 7, 22, 2020 <https://doi.org/10.1186/s40663-020-00224-5>
- Richardson, D.M., Cang Hui, Martin A. Nuñez, Anibal Pauchard (2014) Tree invasions - patterns, processes, challenges and opportunities. *Biol. Invasions* Vol 16: 473–481. DOI 10.1007/s10530-013-0606-9.
- Kakkar.R., K. H. Vinaya Kumar, O.K. Remadevi, M. Manjunatha, B. Saritha. B. Sharma, M. Kiranraddi H. S.Dattaraja and H. S. Suresh (2018) Establishing permanent preservation plots in Bannerghatta National Park for long-term ecological studies to monitor climate change. *My Forest* 54: 19-34.
- Raju, R. (2014). Master Plan of Bannerghatta Biological Park, Bangalore, 2014-15 to 2033 34, Karnataka Forest Department.
- Sagarin R. and Pauchard, A. (2012) *Observation and Ecology*. Island Press: 213 pp.
- Schütz, J.-Ph., Pukkala, T., Donoso, P. and Gadow, K. v. (2012) Historical Emergence and Current Application of CCF. In: T. Pukkala and K. v. Gadow (eds.): *Continuous Cover Forestry*. Book Series *Managing Forest Ecosystems* Vol 24, © Springer Science+Business Media B.V.: p. 1-28.
- Singh, J. S. and R. K. Chaturvedi. (2017a) Diversity of ecosystem types in India: A review. *Proceedings of Indian National Science Academy* 83: 569 – 594.
- Singh, J.S. and R.K Chaturvedi (2017b) *Tropical Dry Deciduous Forest: Research Trends and Emerging Features*. Springer: 238 pages
- Sørensen TA (1948) A method of establishing groups of equal amplitude in plant sociology based on similarity of species content, and its application to analysis of the vegetation on Danish commons. *Biologiske Skrifter Kongelige Danske Videnskabernes Selskab* 5:1-34.
- Spellerberg, Ian, F. and Fedor, Peter, J. (2003) A tribute to Claude Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the ‘Shannon–Wiener’ Index. *Global Ecology & Biogeography* 2003, 12, 177–179.
- Talents LA, Lovett JC, Hall JB, Hamilton AC (2005) Phylogenetic diversity of forest trees in the Usambara mountains of Tanzania: correlations with altitude. *Botanical Journal of the Linnean Society* 149(2):217-228.
- Tjørve, E.(2003) Shapes and functions of species-area curves: a review of possible models. *J. Biogeography* 30: 827-835.
- Wehenkel C, Corral-Rivas JJ, and Gadow K.v. (2014) Quantifying differences between ecosystems with particular reference to selection forests in Durango/Mexico. *Forest Ecology and Management* 316:117-124.
- Williams M. R. (1995) An extreme-value function model of the species incidence and species-area relationship. *Ecology* 76: 2607 – 2616.
- Zeng WeiSheng, Erkki Tomppo, Sean P. Healey and Klaus v. Gadow (2015) The national forest inventory in China: history - results - international context. *Forest Ecosystems*, 2:23.

APPENDIX I: Species tagged in the three permanent preservation plots

Thalewoodhouse								
Species	meanD	meanH	N	BA	mean M	mean D	mean T	mean CV
<i>Acacia concinna</i>	5.8	0	8	0.03	0.78	0.78	0.4	0.46
<i>Albizia odoratissima</i>	37.9	13	1	0.11	1	1	0.9	1
<i>Allophylus cobbe</i>	2.6	3.5	12	0.01	0.91	0.52	0.34	0.47
<i>Ardisia solanacea</i>	2.9	2.7	134	0.11	0.4	0.45	0.38	0.55
<i>Bauhinia racemosa</i>	3	2	2	0	1	0.63	0.32	0.5
<i>Breynia retusa</i>	2.2	2	2	0	1	0.75	0.31	0.51
<i>Breynia vitis-idaea</i>	2.1	2.5	1	0	1	0.5	0.47	0.63
<i>Butea frondosa</i>	17.5	6	1	0.02	1	1	0.87	1
<i>Canthium dicoccum</i>	1.8	3	2	0	0.75	0.38	0.31	0.48
<i>Canthium parviflorum</i>	2.6	2.8	10	0.01	0.88	0.4	0.39	0.47
<i>Careya arborea</i>	12.5	11	3	0.04	0.83	0.92	0.73	0.97
<i>Cassia fistula</i>	5.5	5.1	32	0.14	0.8	0.55	0.48	0.6
<i>Cassia spectabilis</i>	6.3	6	1	0	1	1	0.61	0.56
<i>Celastrus paniculatus</i>	1.1	0	1	0	1	0	0.65	0.49
<i>Cipadessa baccifera</i>	1.9	2.3	404	0.13	0.34	0.47	0.32	0.45
<i>Cordia wallichii</i>	9.4	6.5	31	0.26	0.94	0.89	0.64	0.78
<i>Dalbergia lanceolaria</i>	21.6	15.2	8	0.49	0.91	0.78	0.74	0.85
<i>Dendrocalamus strictus</i>	2.5	2.5	3	0	0.83	0.5	0.4	0.47
<i>Dimocarpus longan</i>	1.5	1.5	1	0	1	0	0.4	0.26
<i>Diospyros melanoxylon</i>	8.8	4.1	4	0.03	1	0.63	0.34	0.38
<i>Diospyros montana</i>	6.8	6	17	0.1	0.97	0.67	0.49	0.69
<i>Embelia tsjeriam-cottam</i>	2.1	1.9	8	0	0.34	0.41	0.37	0.6
<i>Ervatamia beyneana</i>	1.5	1.5	1	0	1	0	0.55	0.86
<i>Erythrina stricta</i>	11.1	8	1	0.01	1	1	0.69	0.85
<i>Erythroxylum monogynum</i>	2	2.9	4	0	0.88	0.13	0.59	0.88
<i>Ficus microcarpa</i>	50.3	25	10	3.6	0.03	0.6	0.59	0.99
<i>Flueggea leucopyrus</i>	1.6	2	1	0	1	0	0.64	0.65
<i>Garuga pinnata</i>	1.6	2	1	0	1	0	0.49	1
<i>Glochidion velutinum</i>	6.1	5.9	119	0.52	0.37	0.51	0.43	0.63
<i>Glochidion zeylanicum</i>	5.2	3.7	31	0.14	0.48	0.58	0.47	0.62
<i>Gmelina arborea</i>	18.3	14	2	0.06	1	0.88	0.53	0.61
<i>Grenia tiliifolia</i>	1.6	2	1	0	1	0.25	0.28	0.31
<i>Helicteres isora</i>	2.2	3.3	4	0	0.75	0.56	0.35	0.34
<i>Hiptage benghalensis</i>	5.3	0	183	0.61	0.69	0.55	0.46	0.64
<i>Holarrhena antidysenterica</i>	3.8	2.3	2	0	1	0.25	0.38	0.58
<i>Ichnocarpus frutescens</i>	2.4	0	19	0.02	0.83	0.22	0.5	0.76
<i>Ipomoea illustris</i>	1.8	0	1	0	1	0.75	0.17	0.15
<i>Ixora nigricans</i>	2.8	2.8	151	0.12	0.74	0.48	0.44	0.63
<i>Jasminum angustifolium</i>	2.3	0	46	0.02	0.95	0.29	0.45	0.61
<i>Mallotus philippensis</i>	4.8	4.4	26	0.1	0.45	0.52	0.46	0.74
<i>Maytenus emarginata</i>	2.2	1.5	2	0	0.75	0.75	0.32	0.8
<i>Memecylon umbellatum</i>	3.1	4.4	7	0.01	0.5	0.64	0.42	0.54

<i>Milium tomentosum</i>	6	5.1	6	0.03	0.67	0.75	0.54	0.73
<i>Mimosa rubicandis</i>	2.5	0	31	0.02	0.73	0.42	0.33	0.43
<i>Mitragyna parvifolia</i>	12.5	10.1	9	0.18	0.31	0.61	0.58	0.82
<i>Olea dioica</i>	4.9	4.5	517	2.19	0.55	0.52	0.42	0.57
<i>Pavetta indica</i>	2	2.9	16	0.01	0.77	0.27	0.49	0.59
<i>Phyllanthus emblica</i>	6.5	5.6	8	0.06	0.93	0.64	0.46	0.54
<i>Phyllanthus polyphyllus</i>	3	3.8	479	0.48	0.29	0.53	0.35	0.45
<i>Phyllanthus reticulatus</i>	4.6	2.7	5	0.01	0.75	0.55	0.41	0.84
<i>Polyalthia cerasoides</i>	3	2.8	91	0.13	0.84	0.45	0.41	0.58
<i>Polyalthia coffeoides</i>	5.3	4.2	10	0.04	0.89	0.61	0.57	0.85
<i>Premna tomentosum</i>	15.7	6	6	0.18	0.38	0.71	0.55	0.75
<i>Pterocarpus marsupium</i>	37.2	17.7	3	0.39	1	1	0.81	0.85
<i>Randia dumetorum</i>	4.8	4.5	93	0.26	0.59	0.63	0.45	0.6
<i>Schleichera oleosa</i>	8.8	6.4	13	0.14	0.75	0.67	0.59	0.76
<i>Scutia myrtina</i>	2.3	0	3	0	0.5	0.42	0.51	0.69
<i>Shorea roxburghii</i>	9.3	8	20	0.26	0.79	0.58	0.52	0.74
<i>Syzygium cumini</i>	20.1	10.6	50	3.62	0.75	0.73	0.63	0.83
<i>Tarenna asiatica</i>	1.9	1.5	1	0	1	0.5	0.27	0.48
<i>Terminalia arjuna</i>	45.1	15.5	42	9.36	0.67	0.8	0.71	0.88
<i>Terminalia bellirica</i>	38.9	15.3	46	7.2	0.87	0.92	0.74	0.89
<i>Terminalia chebula</i>	2.9	16	1	0	1	0.75	0.3	0.3
<i>Toddalia asiatica</i>	2	0	3	0	0.83	0.25	0.46	0.65
<i>Ventilago madraspatana</i>	5.5	0	17	0.06	0.88	0.46	0.47	0.58
<i>Vitex altissima</i>	6.6	7.2	11	0.06	0.91	0.41	0.65	0.82
<i>Wrightia tinctoria</i>	4.1	4	2	0	1	1	0.46	0.38
<i>Ziziphus oenoplia</i>	3	0	281	0.25	0.57	0.53	0.37	0.47
<i>Ziziphus rugosa</i>	2.1	0	4	0	0.88	0.19	0.59	0.85

Bugarikallu								
Species	meanD	meanH	N	BA	mean M	mean D	mean T	mean CV
<i>Acacia chundra</i>	9.31	5.25	189	1.55	0.7	0.8	0.53	0.64
<i>Acacia concinna</i>	2.3	0	22	0.01	0.57	0.36	0.39	0.47
<i>Acacia leucophloea</i>	9.23	6	1	0.01	1	1	0.7	0.79
<i>Albizia amara</i>	3.49	2.57	7	0.01	0.68	0.54	0.43	0.59
<i>Albizia chinensis</i>	1.5	2	5	0	1	0.05	0.41	0.39
<i>Anogeissus latifolia</i>	5.87	5.45	546	1.77	0.57	0.69	0.43	0.52
<i>Argyrea cuneata</i>	1.43	0	3	0	0.75	0.17	0.53	0.68
<i>Atalantia monophylla</i>	1.3	1	1	0	1	0	0.46	0.33
<i>Bauhinia racemosa</i>	10.24	7.57	14	0.14	0.77	0.86	0.61	0.8
<i>Breynia vitis-idaea</i>	2.39	2.94	25	0.01	0.9	0.38	0.42	0.51
<i>Bridelia retusa</i>	6.83	4.75	2	0.01	1	0.63	0.34	0.31
<i>Buchanania axillaris</i>	9.63	4.74	17	0.15	0.82	0.82	0.51	0.6
<i>Cansjera rheedei</i>	1.94	0	5	0	0.8	0.5	0.3	0.41
<i>Canthium dicoccum</i>	4.12	4.11	208	0.4	0.61	0.56	0.44	0.54
<i>Canthium parviflorum</i>	2.42	2.58	36	0.02	0.6	0.38	0.39	0.53
<i>Capparis sepiaria</i>	5.93	0	4	0.01	0.88	0.75	0.51	0.66
<i>Carmona retusa</i>	1.5	1.5	1	0	1	0.75	0.13	0.16
<i>Cassia fistula</i>	3.44	3	29	0.03	0.79	0.52	0.43	0.49

<i>Cassia montana</i>	1.18	2.4	5	0	1	0.05	0.66	0.84
<i>Cassia siamea</i>	11.88	5.5	22	0.39	0.56	0.69	0.47	0.61
<i>Cassine glauca</i>	7.86	5.75	10	0.05	0.55	0.78	0.46	0.56
<i>Celastrus paniculatus</i>	3.45	0	7	0.01	0.93	0.21	0.61	0.54
<i>Cipadessa baccifera</i>	1.5	2	1	0	1	0	0.68	1
<i>Dalbergia lanceolaria</i>	6.59	5.79	17	0.09	0.76	0.79	0.54	0.66
<i>Decalepis hamiltonii</i>	1.7	0	1	0	1	0.25	0.6	0.75
<i>Dendrocalamus strictus</i>	1.81	2.59	149	0.04	0.11	0.9	0.07	0.15
<i>Diospyros melanoxylon</i>	6.22	4.43	74	0.3	0.78	0.7	0.48	0.59
<i>Diospyros montana</i>	5.37	3.64	7	0.03	0.93	0.57	0.51	0.59
<i>Dodonaea viscosa</i>	1.54	2.16	29	0.01	0.76	0.31	0.34	0.5
<i>Erythroxylum monogynum</i>	3.21	3.32	975	0.97	0.38	0.53	0.34	0.42
<i>Eucalyptus globulus</i>	5.97	12	4	0.02	0.25	0.44	0.5	0.73
<i>Ficus benghalensis</i>	27.71	10	11	0.72	0.14	0.57	0.33	0.4
<i>Ficus microcarpa</i>	91.99	9	1	0.66	1	1	0.94	1
<i>Flacourtia indica</i>	3.24	2.95	50	0.06	0.79	0.46	0.42	0.55
<i>Flueggea leucopyrus</i>	3.8	4	1	0	1	0.75	0.35	0.44
<i>Gardenia turgida</i>	1.1	1.5	1	0	1	0.25	0.22	0.33
<i>Grewia asiatica</i>	6.76	6	2	0.01	0.75	0.88	0.5	0.61
<i>Grewia hirsuta</i>	1.1	1.5	1	0	1	0	0.69	0.48
<i>Grewia orbiculata</i>	3.06	2.84	82	0.08	0.69	0.44	0.42	0.51
<i>Gymnema sylvestre</i>	1.78	0	4	0	1	0.31	0.32	0.47
<i>Holarrhena antidysenterica</i>	3.12	3.11	49	0.05	0.67	0.58	0.42	0.52
<i>Ixora nigricans</i>	3.2	3.07	1033	1.02	0.45	0.53	0.35	0.43
<i>Jasminum angustifolium</i>	1.7	0	145	0.04	0.83	0.27	0.43	0.57
<i>Lagerstroemia parviflora</i>	6.34	4.75	20	0.08	0.65	0.7	0.4	0.49
<i>Madhuca indica</i>	7.46	5.87	19	0.14	0.39	0.62	0.4	0.47
<i>Maytenus emarginata</i>	2.23	2.29	319	0.15	0.48	0.43	0.37	0.5
<i>Memecylon umbellatum</i>	2.46	5	11	0.01	0.41	0.48	0.42	0.52
<i>Naringi crenulata</i>	5.34	4.5	4	0.01	0.94	0.88	0.51	0.67
<i>Ochna obtusata</i>	3.74	3.23	215	0.27	0.61	0.52	0.37	0.45
<i>Phyllanthus indofischeri</i>	11.62	7	1	0.01	1	1	0.75	0.88
<i>Polyalthia cerasoides</i>	3.81	3.86	18	0.03	0.97	0.57	0.47	0.56
<i>Polyalthia coffeoides</i>	2.55	2.88	4	0	0.69	0.5	0.51	0.56
<i>Premna tomentosa</i>	3.06	3.22	25	0.02	0.39	0.5	0.39	0.4
<i>Pterocarpus marsupium</i>	9.5	6.06	8	0.07	1	0.84	0.71	0.91
<i>Pterolobium hexapetalum</i>	2.08	0.01	400	0.17	0.51	0.43	0.34	0.47
<i>Randia dumetorum</i>	2.45	2.26	27	0.02	0.61	0.34	0.41	0.49
<i>Rapanea nighiana</i>	7.32	5	2	0.01	0.75	0.88	0.35	0.33
<i>Santalum album</i>	2.56	3.67	3	0	1	0.17	0.4	0.62
<i>Scolopia crenata</i>	5.09	6	1	0	1	0.75	0.35	0.45
<i>Scutia myrtina</i>	2.14	0	35	0.02	0.72	0.39	0.39	0.49
<i>Secamone emetica</i>	1.5	0	1	0	1	0	0.39	0.41
<i>Semecarpus anacardium</i>	13.53	6.75	6	0.09	0.75	0.88	0.59	0.79
<i>Shorea roxburghii</i>	5.06	5.5	12	0.03	0.33	0.63	0.44	0.49
<i>Soyimida febrifuga</i>	8.65	5.75	2	0.01	1	1	0.57	0.72
<i>Stereospermum suaveolens</i>	8.06	6.63	4	0.03	0.88	0.69	0.6	0.67
<i>Strychnos potatorum</i>	6.44	3.78	9	0.04	0.89	0.56	0.53	0.63

<i>Tarenna asiatica</i>	1.77	2.62	313	0.09	0.56	0.33	0.39	0.53
<i>Terminalia chebula</i>	9.44	6.97	15	0.11	0.72	0.8	0.56	0.7
<i>Terminalia paniculata</i>	8.52	5.5	4	0.03	1	0.81	0.62	0.73
<i>Toddalia asiatica</i>	1.63	0	10	0	0.95	0.23	0.42	0.46
<i>Ventilago maderaspatana</i>	3.7	0	5	0.01	0.75	0.8	0.33	0.52
<i>Vitex altissima</i>	5.19	6.33	12	0.03	0.67	0.65	0.46	0.59
<i>Wrightia tinctoria</i>	6.65	7.5	6	0.05	0.13	0.75	0.55	1
<i>Ziziphus oenopolia</i>	2.19	0.29	62	0.03	0.71	0.35	0.43	0.56
<i>Ziziphus rugosa</i>	2.9	0	1	0	1	0	0.36	0.22
<i>Ziziphus xylopyrus</i>	2.4	3.5	4	0	0.88	0.5	0.49	0.41

Doresanipalya								
Species	meanD	meanH	N	BA	mean M	mean D	mean T	mean CV
<i>Acacia auriculiformis</i>	9.5	7.4	117	1.32	0.55	0.66	0.56	0.73
<i>Albizia amara</i>	6	8	2	0.01	0.75	0.5	0.63	0.83
<i>Albizia lebbeck</i>	11.2	5.4	33	0.54	0.85	0.77	0.6	0.78
<i>Albizia odoratissima</i>	4	3.5	1	0	1	0.75	0.32	0.34
<i>Anacardium occidentale</i>	5.2	2.8	23	0.08	0.12	0.58	0.41	0.52
<i>Annona squamosa</i>	1.1	2.5	1	0	1	0	0.31	0.32
<i>Argyrea cuneata</i>	1.2	0	1	0	1	0.25	0.48	0.98
<i>Argyrea sericea</i>	1.2	0	11	0	0.91	0.2	0.45	0.73
<i>Bambusa bambos</i>	4.9	9.3	398	0.8	0	1	0	0
<i>Breynia vitis-idaea</i>	1.4	2.4	79	0.01	0.64	0.43	0.27	0.41
<i>Canthium parviflorum</i>	1.3	1.8	3	0	0.83	0.25	0.49	1
<i>Cassia fistula</i>	4.9	3.1	7	0.03	0.58	0.67	0.34	0.5
<i>Cassia siamea</i>	17.4	9.9	9	0.22	0.42	0.67	0.45	0.51
<i>Cassia spectabilis</i>	3.4	5	27	0.03	0.47	0.54	0.38	0.49
<i>Cassine paniculata</i>	7.1	4.3	4	0.02	0.88	0.81	0.53	0.58
<i>Dendrocalamus strictus</i>	2.9	3.4	794	0.53	0.1	0.94	0.06	0.14
<i>Diospyros melanoxylon</i>	3.4	2.6	29	0.04	0.73	0.59	0.39	0.53
<i>Embelia viridifolia</i>	1.1	0	1	0	0.75	0.25	0.4	0.73
<i>Erythroxylum monogynum</i>	2.3	2.7	45	0.02	0.58	0.54	0.35	0.43
<i>Eucalyptus tereticornis</i>	13.7	10.8	220	4.86	0.54	0.69	0.6	0.8
<i>Flacourtia indica</i>	1.5	1.5	1	0	1	0.25	0.37	0.44
<i>Flueggea leucopyrus</i>	2.1	2.7	25	0.01	0.51	0.55	0.23	0.26
<i>Grevillea robusta</i>	12	7.2	3	0.05	1	0.92	0.64	0.77
<i>Gymnema sylvestris</i>	1.4	0	30	0	0.9	0.2	0.43	0.56
<i>Homalium zeylanicum</i>	8.9	6	1	0.01	1	1	0.76	0.89
<i>Ixora brachiata</i>	1.3	1.5	1	0	1	0	0.66	0.76
<i>Ixora nigricans</i>	1.1	1.5	1	0	1	0.25	0.56	1
<i>Jacaranda mimosifolia</i>	3.9	6	2	0	0.75	0.88	0.4	0.45
<i>Lannea coromandelica</i>	4.6	3.4	9	0.02	0.84	0.81	0.5	0.62

<i>Leucaena leucocephala</i>	2.5	4.1	43	0.06	0.63	0.37	0.37	0.4
<i>Mallotus philippensis</i>	1	2	1	0	1	0	0.35	0.5
<i>Ochna obtusata</i>	4.2	2.8	9	0.02	0.78	0.69	0.31	0.33
<i>Pongamia pinnata</i>	5.5	5.5	12	0.06	0.73	0.56	0.48	0.73
<i>Psidium guajava</i>	3.5	2.5	2	0	0.75	0.88	0.38	0.4
<i>Pterocarpus marsupium</i>	4.8	4.4	72	0.23	0.72	0.61	0.5	0.67
<i>Santalum album</i>	2.1	3.4	1388	0.57	0.37	0.45	0.36	0.5
<i>Scutia myrtina</i>	1.6	0	27	0.01	0.92	0.19	0.46	0.59
<i>Shorea roxburghii</i>	8.4	4.9	398	3.91	0.59	0.68	0.47	0.61
<i>Syzygium cumini</i>	6.4	5.7	3	0.01	0.83	0.33	0.44	0.66
<i>Tamarindus indica</i>	8.3	5.7	13	0.1	0.81	0.71	0.54	0.71
<i>Terminalia arjuna</i>	6.7	4	1	0	1	1	0.82	1
<i>Terminalia chebula</i>	5.4	4.5	1	0	1	1	0.68	0.74
<i>Terminalia paniculata</i>	19.1	11	1	0.03	1	1	0.89	1
<i>Tylophora indica</i>	1.3	0	5	0	0.9	0.15	0.4	0.5
<i>Ziziphus mauritiana</i>	6.4	4.5	6	0.02	0.75	0.88	0.59	0.68
<i>Ziziphus oenoplia</i>	2.7	0	505	0.38	0.35	0.53	0.36	0.48

Figures

Figure 1

Distribution of forest types in India (map kindly provided by the Forest Survey of India, 2019). The study areas are located in the vicinity of Bengaluru in the South-Eastern part of the State of Karnataka.

Figure 2

Location of the three study sites to the south of the Bengaluru city center. Google map images of the study sites and their immediate surroundings are shown in the three circles.

Figure 3

A general impression of the spatial species mix and tree size distribution in the three study areas. Each species has a unique color across all three study sites. The subdivision into smaller cells facilitates analysis of the spatial distribution (and scale dependence) of particular patterns.

Figure 4

Species Abundance Distributions of the three study areas. When plotted in this way, relative species abundances from very different data sets show similar patterns.

Figure 5

The relationships between species-specific variables in the three plots. Shown are the number of trees per ha and the mean neighborhood mingling with the estimated non-linear model below (upper row); the mean dbh (cm) and the mean neighborhood Dominance with the estimated Monod model (below).